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Correlations among industrial traits in oat cultivars grown in different locations of Brazil

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Abstract

Oat is an important cereal for human consumption and is increasing its share of the functional food market every year. Correlation estimates and path analyses based on data from different environments can help to identify the most important traits to increase industrial yield potential of oat genotypes. This can facilitate the development of strategies to achieve higher genetic gains for grain quality. Thus, this study aimed to estimate the correlations between traits related to industrial performance of oat cultivars grown in different environments. Also, the genetic correlation coefficients were partitioned by path analysis in in direct and indirect effects on industrial yield of grains, in order to identify traits that could be adopted in indirect selection strategies. In the crop seasons of 2007, 2008 and 2009, 15 oat cultivars were grown in two different locations, following a randomized complete block design with four replications. Variables related to grain yield, quality and industrial yield were evaluated. In each location the phenotypic, genetic and environmental correlations among traits were estimated, followed by partitioning of genetic correlations into direct and indirect effects on industrial grain yield through path analysis. The performance and the relationships between traits were modified in response to environmental effects, which can compromise the effectiveness of indirect selection. Hectoliter mass did not show a causal association with industrial yield. Grain yield, index of grains larger than 2 mm and number of grains per panicle presented positive direct effects on industrial yield of grains, however just the grain yield showed a strong and stable association. Thus, grain yield seems to be the most successful process of indirect selection for the genetic improvement of industrial yield of grains.

Keywords: *Avena sativa* L., cultivation environment, grain quality, indirect selection; path analysis.
Abbreviations: MTG_mass of a thousand grains; HM_hectoliter mass; NFT_number of fertile tillers per linear meter; NGP_number of grains per panicle; MGP_mass of grains per panicle; GY_grain yield; IG ≥ 2 mm_index of grains larger than 2 mm; MG ≥ 2 mm_mass of 300 whole grains larger than 2 mm wide; CM ≥ 2 mm_caryopsis mass of 300 dehulled grains larger than 2 mm wide; PR_peeling rate; IYG_industrial yield of grains; r_P_phenotypic correlation; r_G_genotypic correlation; r_E_environmental correlation; P_{IYG}_direct effect of explanatory characters on the basic variable IYG.

Introduction

Grain industrial yield in oats can be defined by the fraction of caryopses of grains with a diameter equal or larger than two millimeters in the total mass of grains harvested. Overall, the characterization of oat genotypes for grain quality and the breeding strategies aiming high industrial quality focus on hectoliter mass performances (Holland, 1997; De Francisco et al., 2002; Buerstmayr et al., 2007; Zute et al., 2010). However, along with the hectoliter mass, the mechanical hulling resistance, the grain width and the fraction of caryopsis can be essential to determine the grain industrial fitness of an oat cultivar (Doehlert et al., 1999; Doehlert et al., 2009).

The selection efficiency of high industrial yield oat genotypes can be reduced when carried out in early generations and performed directly on phenotype. Similar to grain yield, the industrial yield represents a complex character, difficult to measure, defined by a large set of genes, and therefore strongly influenced by the effects of growing environment (Tamm, 2003; Peterson et al., 2005; Crestani et al., 2010; Dumlupinar et al., 2011). In this sense, the selection of oat genotypes with industrial quality could be more effective when applied indirectly, adopting highly correlated traits as targets of selection that are easier to measure and/or show high heritability (Benin et al., 2005; Lorencetti et al., 2006).

The dynamic of characters related to industrial yield in oat cultivars can be assessed by correlation and path analyses. Correlation is a measure of the degree to which variables vary together or a measure of intensity of association (Steel and Torrie, 1980). Meanwhile, path analysis studies allow one to identify the direct effect of explanatory variables on a basic variable after removing the influence of all other explanatory variables included in the analysis (Wright, 1921). These evaluations can help electing the most important traits to determine the industrial yield potential of oat genotypes and assist in developing strategies to achieve genetic gains.

To our knowledge, this is the first time that the performance of Brazilian oat cultivars regarding industrial yield is partitioned into its direct and indirect components.

The genetic gains to be obtained via artificial selection are heavily dependent on the combining ability of parents used in the hybridization (Benin et al., 2005; Bertan et al., 2007), indicating a need for an accurate assessment of genotype potentials in oat breeding programs. Also, heritability and correlation estimates are very dependent on the evaluated genetic constitution and the environment under assessment (Souza et al., 1998; Benin et al., 2005; Lorencetti et al., 2006). Therefore, correlation estimates between characters of quality and industrial yield of grains in oat are modified in response to environmental conditions, but major characters show more stable correlations and consequently may be considered for indirect selections strategies. Thus, this study aimed to estimate the correlations between characters related to industrial performance in oat cultivars grown in different environments. Also, the genetic correlation coefficients were partitioned in direct and indirect effects on industrial yield of grains by path analysis in order to identify the most important traits that could be adopted in indirect selection strategies.

Results and Discussions

Performance of oats for traits related to industrial yield of grains

The cultivating environment showed a significant effect on the phenotypic expression of all characters evaluated considering the average performance of oat cultivars (Table 2). The observed results agree with reports showing that grain and industrial yield components in oats are influenced by environmental conditions and correlations tend to be likewise variable (Holland, 1997; Buerstmayr et al., 2007; Zute et al., 2010; Martinez et al., 2010; Dumlupinar et al., 2011). Therefore, one can evaluate oat genotypes along several environments in order to assess which associations between traits are more stable and significant across environments, assisting breeder decisions.

Correlations between traits as response to environmental effects

Considering the performance of oat cultivars cultivated in Augusto Pestana and Capão do Leão for the set of cultivating seasons (2007, 2008 and 2009), the phenotypic (r_P), genetic (r_G) and environmental (r_E) correlations between traits were different in magnitude and/or in direction considering the locations (Table 3). Such inconsistency was also observed when comparing the results between the locations tested in regard to the partitioning of genetic correlations (r_G) into direct and indirect effects on industrial yield of grains (IYG, basic variable) by the explanatory variables: number of fertile tillers per linear meter (NFT), grain yield (GY), mass of thousand grains (MTG), hectoliter mass (HM), mass of grains per panicle (MGP), number of grains per panicle (NGP), index of grains larger than 2 mm (IG≥2 mm), mass of 300 whole grains larger than 2 mm wide (MG≥2 mm), caryopsis mass of 300 dehulled grains larger than 2 mm wide (CM≥2 mm), and peeling rate (PR) (Table 4).

Capão do Leão is located in a coastal plain region in the Southern part of Rio Grande do Sul (RS) State and, consequently, has distinctive characteristics with regard to climate, landscape, and soil composition compared to Augusto Pestana, which is located on a plateau of volcanic basalt stone with landscape of moderate ripples in the Northwest of RS. Thus, in the growing season, higher rainfall and average temperatures were observed in Augusto Pestana (Table 1). Therefore, differences in location specific features could have led to different effects on the overall oat cultivar performances, and on the observed associations between the traits. Other studies report that performance of oat grain characters of quality and yield such as grain yield, hectoliter mass, index of grains larger than 2 mm, peeling rate, caryopsis mass and caryopsis yield are affected by growing site environmental conditions, i.e., daily temperature and precipitation (Zute et al., 2010) and their correlations are also modified (Buerstmayr et al., 2007; Crestani et al., 2010).

The correlation inconsistencies observed can be attributed to environmental effect modifications and to the different physiological mechanisms involved in the expression of environment responsive characters (Falconer and Mackay, 1996). These results are in agreement with the fact that correlation and heritability estimates are restricted to the evaluated genetic constitution and to the environment under assessment (Benin et al., 2005; Zute et al., 2010; Crestani et al., 2010)., The analysis of correlations among traits and the consequent definition of strategies that will assist in the genetic improvement of oat plants should be made taking into account the location features, thus increasing the possibilities of genetic gain with the selection.

Although a number of significant correlations of low magnitude were detected in this work, a t test at $p \leq 0.05$ (values superior to 0.16) and $p \leq 0.01$ (values superior to 0.22), strategies of indirect selection based on these associations can lead to inefficient process of genetic gains, since the correlation coefficients can be result of a weak genetic association (genetic linkage and pleiotropy) between traits. Therefore, only the strongest associations between the characters ($r \geq 0.40$ to 0.99) are covered in the results and discussion section.

Environmental correlations

Most of the significant environment correlations observed were positive (Table 3). The environment represents a cause of correlation when two characters are influenced by the same differences in the environmental conditions (Falconer and Mackay, 1996). In both locations, positive and high environmental correlations between MG ≥ 2 mm and CM ≥ 2 mm (Augusto Pestana, r_E: 0.90; Capão do Leão, r_E: 0.85), and between MGP and NGP (Augusto Pestana, r_E: 0.79; Capão do Leão, r_E: 0.76) were observed. Likewise, the environmental correlations between IYG and GY, IG ≥ 2 mm, CM ≥ 2 mm and with PR were positive for both locations, with medium to high magnitudes (r_E from 0.36 to 0.87).

Phenotypic and genotypic correlations between traits, the direct and indirect effects on industrial yield of grains and its consequences on oat genetic improvement

The characters with high level of genetic and phenotypic correlation can be considered for selection strategies. However, only the genetic correlations involving an association of heritable nature may therefore contribute to the effective targeting of improvement programs (Falconer and Mackay, 1996). Thus, the genetic correlation coefficients were partitioned into their direct and indirect effects on IYG through path analysis in order to assess if the correlation between two variables was due to a cause and effect or was determined by the influence of other variables (Table 4).

Table 1. Information on soil chemical properties and climate conditions observed in the Counties of Augusto Pestana and Capão do Leão, Rio Grande do Sul State, Brazil, in the crop seasons 2007, 2008 and 2009.

Crop Season	Location	Soil chemical properties				
		Clay (%)	SMP index	O.M. (%)	P (mg dm^{-3})	K (mg dm^{-3})
2007	Augusto Pestana	50.0	6.6	3.2	31.0	385.0
	Capão do Leão	24.0	6.8	2.2	29.1	143.0
2008	Augusto Pestana	54.0	6.2	2.9	26.0	292.0
	Capão do Leão	16.0	6.8	1.5	8.6	64.0
2009	Augusto Pestana	56.0	6.4	2.8	25.0	215.0
	Capão do Leão	21.0	6.5	2.1	19.7	80.0
Crop Season	Location	Average climate conditions in the growing period[1]				
		Maximum temperature (ºC)	Minimum temperature (ºC)	Medium temperature (ºC)	Accumulated precipitation (mm)	
2007	Augusto Pestana	23.3	11.4	17.3	863.0	
	Capão do Leão	19.5	10.8	15.7	798.8	
2008	Augusto Pestana	23.1	11.3	17.2	963.6	
	Capão do Leão	20.4	11.7	16.0	575.3	
2009	Augusto Pestana	22.8	9.7	16.2	1407.4	
	Capão do Leão	20.0	11.0	15.0	952.0	

[1]Data related to the period from June to November in each year. Data collected by the Agro-climatic Station of the Federal University of Pelotas/Embrapa Temperate Climate, Capão do Leão, RS; and Regional Institute of Rural Development -IRDER/UNIJUÍ; Augusto Pestana, RS.

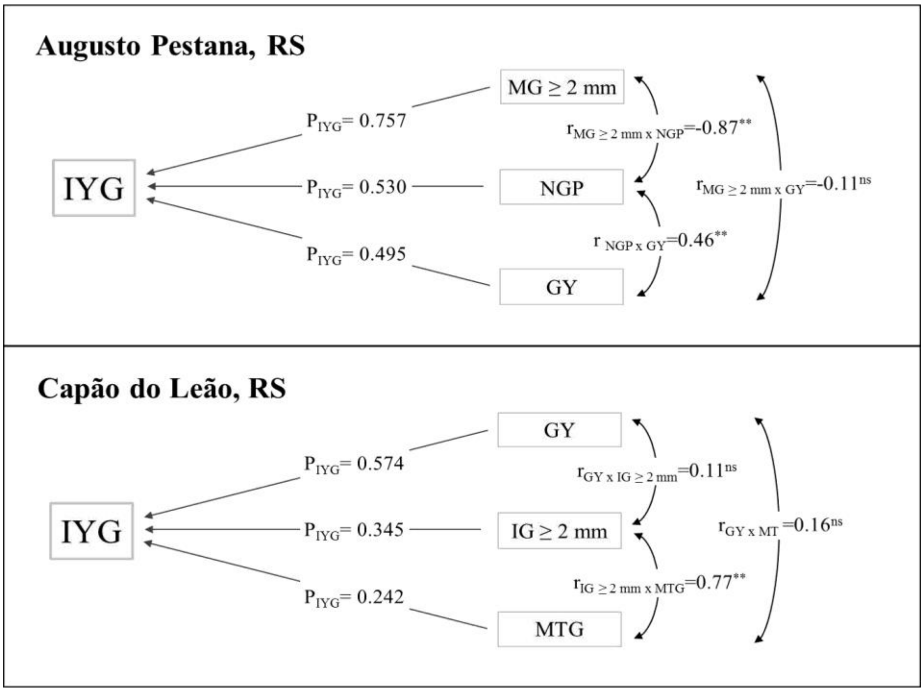

Fig 1. Illustrative diagram showing the direct and indirect effects of the most important explanatory variables on the basic variable industrial yield of grains (IYG) in oat cultivars grown in Augusto Pestana and Capão do Leão, Rio Grande do Sul State, Brazil, in the crop seasons 2007, 2008 and 2009. P_{IYG}: direct effect of explanatory characters on the basic variable IYG; r: genotypic correlation coefficient between explanatory characters; MTG: mass of thousand grains; GY: grain yield; IG ≥ 2 mm: index of grains larger than 2 mm; MG ≥ 2 mm: mass of 300 whole grains larger than 2 mm wide.

A causal diagram illustrating the direct and indirect effects of the most important explanatory variables on the basic variable IYG considering the cultivation of oat cultivars in each local evaluated is shown in Fig.1.

The coefficients of determination (R^2) of the path analysis model were high in Augusto Pestana (0.964) and Capão do Leão (0.896), indicating that the explanatory variables explained a major part of the variation observed in the basic variable IYG (Table 4). Considering the IYG's components, the largest genetic correlation was IYG x IG ≥ 2 mm (r_G= 0.77), followed by IYG x CM ≥ 2 mm (r_G= 0.68), IYG x MG ≥ 2 mm (r_G= 0.64), and IYG x GY (r_G= 0.61) in Augusto Pestana. Meanwhile, in Capão do Leão, the highest correlation was IYG x GY (r_G= 0.89), followed by the relation between IYG x IG ≥ 2 mm (r_G=0.50), IYG x NFT (r_G=0.50), IYG x MTG (r_G=0.47) and IYG x PR (r_G=0.41), as shown on Table 2. Initially, in Augusto Pestana, characters related to volume and mass of grains (IG ≥ 2 mm, CM ≥ 2 mm and MG ≥ 2 mm) seem to be closely associated to industrial yield of grains, besides grain yield. Meanwhile, in Capão do Leão, it is possible to highlight the grain yield as the most associated character to industrial yield, followed by grain yield's direct components (NFT and MTG) and

Table 2. Variation of performance (average ± standard deviation) regarding different characters related to oat grain industrial yield of cultivars growing in the Counties of Augusto Pestana and Capão do Leão, Rio Grande do Sul State, Brazil, in the crop seasons 2007, 2008 and 2009.

Character	Location of cultivation/ Crop season					
	Augusto Pestana			Capão do Leão		
	2007	2008	2009	2007	2008	2009
HM** (100 kg L^{-1})	38.15 ± 4.31	39.13 ± 3.85	38.72 ± 2.33	55.41 ± 4.71	40.98 ± 5.79	50.75 ± 2.18
MTG** (g)	28.70 ± 2.94	28.00 ± 3.80	29.08 ± 3.64	35.39 ± 4.09	24.87 ± 4.30	36.48 ± 4.46
NFT** (unit)	61.03 ± 16.34	64.99 ± 7.93	69.42 ± 10.15	58.72 ± 10.93	72.97 ± 19.82	43.73 ± 10.35
NGP** (unit)	53.68 ± 14.80	86.52 ± 13.53	72.93 ± 16.29	51.91 ± 10.52	80.12 ± 15.44	80.85 ± 14.13
MGP** (g)	1.51 ± 0.31	2.29 ± 0.37	2.21 ± 0.52	1.70 ± 0.33	1.96 ± 0.46	2.65 ± 0.44
GY** (kg ha^{-1})	1541.52 ± 335.83	2443.08 ± 427.49	2888.23 ± 391.12	1608.86 ± 394.97	2148.87 ± 769.33	1631.93 ± 365.35
IG≥2mm** (dimensionless)	0.69 ± 0.10	0.63 ± 0.11	0.74 ± 0.09	0.82 ± 0.07	0.71 ± 0.19	0.91 ± 0.05
MG≥2mm** (g)	12.95 ± 1.56	9.71 ± 1.11	10.10 ± 1.52	11.24 ± 1.06	9.09 ± 1.35	10.96 ± 1.19
CM≥2 mm** (g)	9.56 ± 1.26	6.50 ± 0.91	7.25 ± 1.28	8.39 ± 0.78	6.06 ± 1.12	7.98 ± 0.98
PR** (dimensionless)	0.74 ± 0.03	0.67 ± 0.05	0.72 ± 0.05	0.75 ± 0.03	0.66 ± 0.05	0.73 ± 0.04
IYG** (kg ha^{-1})	786.92 ± 220.79	1043.49 ± 316.95	1527.18 ± 305.88	987.41 ± 272.99	1035.26 ± 544.23	1079.23 ± 252.43

HM: hectoliter mass, MTG: mass of thousand grains, NFT: number of fertile tillers per linear meter, NGP: number of grains per panicle, MGP: mass of grains per panicle, GY: grain yield, IG≥2mm: index of grains larger than 2 mm, MG≥2mm: mass of 300 whole grains larger than 2 mm wide, CM≥2 mm: caryopsis mass of 300 dehulled grains larger than 2 mm wide, PR: peeling rate, IYG: industrial yield of grains. **Significant at **p ≤ 0.01** by F-test regarding the factor environment of cultivation (location + crop season).

industrial yield of grains' direct components (IG ≥ 2 mm and PR). Assessing the partitioned genetic correlations by path analysis (Table 4), positive direct effects of GY on the IYG were observed in both locations, with values slightly lower than the genetic correlations found, but higher than the variable's residue effect (Augusto Pestana: r_G= 0.605, direct effect= 0.495; Capão do Leão: r_G= 0.892, direct effect= 0.574). Oat grain yield represents a character of high complexity, because it is controlled by a large number of genes, which interact strongly with the cultivating environment (Buerstmayr et al., 2007; Zute et al., 2010; Crestani et al., 2010). However, number of fertile tillers per area, number of grains per panicle and average mass of grains are the direct components of grain yield in the oat crop and therefore very important. Grain yield in oat is a sequential process where the number of panicles produced per plant is defined firstly, followed by the number of grains fertilized per inflorescence and by the dry mass of grains produced per panicle (Almeida et al., 2003). In this evaluation, the association between the direct components of grain yield (NFT, NGP and MTG) changed according to location, indicating a compensation effect in the performance of components, reflecting directly on industrial yield (Tables 3 and 4). In Capão do Leão, NFT showed positive correlations with IYG (r_G= 0.502), and a small positive direct effect on this variable (0.295). In this location, the NFT had a considerable positive indirect effect on the dependent variable IYG via GY (0.406), where the correlation between NFT and GY was high (r_G= 0.710). On the other hand, in Augusto Pestana, no considerable direct effect of NFT on IYG was identified (-0.004), and the negative correlation between NFT and IYG (r_G= -0.879) was due to the negative effects mainly via IG ≥ 2 mm (-0.196), MG ≥ 2 mm (-0.571) and via CM ≥ 2 mm (-0.257).

The character MTG showed no expressive genetic correlation with GY in both locations, as also observed in evaluations of oat cultivar performances over different environments (Peterson et al., 2005; Buerstmayr et al., 2007). Meanwhile, positive correlations of MTG with IYG were detected in Capão de Leão (r_G= 0.467) and in Augusto Pestana (r_G= 0.348). However, a small positive direct effect on IYG (0.242) in Capão do Leão, and negative direct effect in Augusto Pestana (-0.260), reaffirming the significant environmental effects on the phenotypic expression and character relationships. In Augusto Pestana, GY was positively correlated with NGP (r_G= 0.46) and with MGP (r_G= 0.62), while in Capão do Leão these correlations were negative (r_G= -0.34 and -0.38, respectively). Also, in both locations, Augusto Pestana and Capão do Leão, positive genetic correlations of 0.62 and 0.52, respectively, were observed between NGP and MGP (Table 3). Likewise, other studies on oat crops have shown the occurrence of high positive association between the panicle mass and the number of grains per panicle, and less strong positive associations between panicle mass and mass of grains per panicle (Chapko and Brinkmann, 1991; Hartwig et al., 2006; Lorencetti et al., 2006). These results suggest that the major effect on panicle mass increase is mainly caused by the increment of the number of grains per panicle, with a minor effect on the mean grain mass increase. In most of the improvement carried out with cereals in the world, the increment in the number of grains per unit area seems to represent the most important component in the increase of grain yield (Feil, 1992). The indirect selection for increasing grain yield based on the number of grains per panicle can lead to small grain size high yield potential oat genotypes, since in cereal crops the number of grains per inflorescence tends to show negative correlation with the average grain mass (Dumlupinar et al., 2011; Sinclair and Jamieson, 2008). As a consequence, this

Table 3. Estimates of phenotypic (r_P), genetic (r_G) and environmental correlations (r_E) between characters related to quality and yield of grains in oat cultivars grown in Augusto Pestana (below diagonal) and Capão do Leão (upper diagonal), Rio Grande do Sul State, Brazil, in the crop seasons 2007, 2008 and 2009.

Character	HM	MTG	NFT	NGP	MGP	GY	IG≥ 2mm	MG≥ 2mm	CM≥ 2mm	PR	IYG
	Phenotypic correlation coefficient (r_P)										
HM	---	-0.12^{ns}	0.74^{**}	-0.49^{**}	-0.50^{**}	0.34^{**}	-0.23^{**}	0.01^{ns}	0.22^{**}	0.59^{**}	0.28^{**}
MTG	0.10^{ns}	---	-0.13^{ns}	-0.41^{**}	0.39^{**}	0.15^{ns}	0.74^{**}	0.95^{**}	0.85^{**}	-0.12^{ns}	0.44^{**}
NFT	0.31^{**}	-0.22^{**}	---	-0.69^{**}	-0.69^{**}	0.59^{**}	-0.19^{*}	-0.01^{ns}	0.12^{ns}	0.40^{**}	0.43^{**}
NGP	-0.02^{ns}	-0.67^{**}	0.07^{ns}	---	0.54^{**}	-0.30^{**}	-0.15^{ns}	-0.56^{**}	-0.64^{**}	-0.32^{**}	-0.34^{**}
MGP	-0.18	-0.04^{ns}	-0.11^{ns}	0.65^{**}	---	-0.32^{**}	0.42^{**}	0.27^{**}	0.13^{ns}	-0.33^{**}	-0.10^{ns}
GY	0.13^{ns}	-0.24^{**}	0.06^{ns}	0.38^{**}	0.30^{**}	---	0.10^{ns}	0.09^{ns}	0.15^{ns}	0.20^{*}	0.89^{**}
IG≥2mm	0.02^{ns}	0.66^{**}	-0.44^{**}	-0.42^{**}	0.01^{ns}	-0.03^{ns}	---	0.59^{**}	0.47^{**}	-0.22^{**}	0.50^{**}
MG≥2mm	0.14^{ns}	0.84^{**}	-0.29^{**}	-0.72^{**}	-0.20^{*}	-0.09^{ns}	0.80^{**}	---	0.92^{**}	-0.05^{ns}	0.34^{**}
CM≥2mm	0.33^{**}	0.69^{**}	-0.21^{*}	-0.58^{**}	-0.24^{**}	0.07^{ns}	0.65^{**}	0.93^{**}	---	0.35^{**}	0.41^{**}
PR	0.60^{**}	-0.01^{ns}	0.14^{ns}	0.00^{ns}	-0.22^{**}	0.44^{**}	-0.05^{ns}	0.25^{**}	0.59^{**}	---	0.25^{**}
IYG	0.15^{ns}	0.34^{**}	-0.30^{**}	-0.07^{ns}	0.12^{ns}	0.62^{**}	0.73^{**}	0.58^{**}	0.64^{**}	0.41^{**}	---
	Genotypic correlation coefficient (r_G)										
HM	---	-0.15^{ns}	0.90^{**}	-0.58^{**}	-0.61^{**}	0.36^{**}	-0.28^{**}	-0.02^{ns}	0.20^{*}	0.62^{**}	0.29^{**}
MTG	0.09^{ns}	---	-0.17^{*}	-0.45^{**}	0.41^{**}	0.16^{*}	0.77^{**}	0.99^{**}	0.88^{**}	-0.14^{ns}	0.47^{**}
NFT	0.81^{**}	-0.59^{**}	---	-0.78^{**}	-0.82^{**}	0.71^{**}	-0.24^{**}	-0.01^{ns}	0.13^{ns}	0.46^{**}	0.50^{**}
NGP	-0.03^{ns}	-0.82^{**}	0.15^{ns}	---	0.52^{**}	-0.34^{**}	-0.16^{*}	-0.61	-0.70^{**}	-0.36^{**}	-0.39^{**}
MGP	-0.29^{**}	-0.13^{ns}	-0.62^{**}	0.62^{**}	---	-0.38^{**}	0.47^{**}	0.27^{**}	0.12^{ns}	-0.39^{**}	-0.13^{ns}
GY	0.14^{ns}	-0.31^{**}	-0.06^{ns}	0.46^{**}	0.41^{**}	---	0.11^{ns}	0.08^{ns}	0.14^{ns}	0.20^{*}	0.89^{**}
IG≥2mm	0.02^{ns}	0.70^{**}	-0.99^{**}	-0.49^{**}	-0.01^{ns}	-0.01^{ns}	---	0.61^{**}	0.48^{**}	-0.26^{**}	0.50^{**}
MG≥2mm	0.16^{*}	0.92^{**}	-0.75^{**}	-0.87^{**}	-0.37^{**}	-0.11^{ns}	0.84^{**}	---	0.92^{**}	-0.07^{ns}	0.35^{**}
CM≥2mm	0.36^{**}	0.74^{**}	-0.52^{**}	-0.70^{**}	-0.42^{**}	0.08^{ns}	0.68^{**}	0.93^{**}	---	0.33^{**}	0.41^{**}
PR	0.67^{**}	-0.05^{ns}	0.39^{**}	-0.01^{ns}	-0.35^{**}	0.54^{**}	-0.07^{ns}	0.30^{**}	0.62^{**}	---	0.24^{**}
IYG	0.16^{*}	0.35^{**}	-0.88^{**}	-0.09^{ns}	0.12^{ns}	0.61^{**}	0.77^{**}	0.64^{**}	0.68^{**}	0.39^{**}	---
	Environmental correlation coefficient (r_E)										
HM	---	0.20^{*}	0.04^{ns}	0.06^{ns}	0.10^{ns}	0.24^{**}	0.14^{ns}	0.31^{**}	0.41^{**}	0.37^{**}	0.28^{**}
MTG	0.20^{*}	---	0.16^{*}	0.08^{ns}	0.16^{*}	0.12^{ns}	0.30^{**}	0.26^{**}	0.29^{**}	0.19^{*}	0.24^{**}
NFT	-0.06^{ns}	0.06^{ns}	---	-0.19^{*}	-0.08^{ns}	0.00^{ns}	0.15^{ns}	-0.03^{ns}	0.02^{ns}	0.07^{ns}	0.08^{ns}
NGP	0.02^{ns}	0.07^{ns}	0.05^{ns}	---	0.76^{**}	0.07^{ns}	-0.05^{ns}	0.20^{*}	0.19^{*}	0.09^{ns}	0.06^{ns}
MGP	0.10^{ns}	0.21^{*}	0.11^{ns}	0.79^{**}	---	0.06^{ns}	0.03^{ns}	0.26^{**}	0.26^{**}	0.13^{ns}	0.10^{ns}
GY	0.10^{ns}	0.06^{ns}	0.18^{*}	0.11^{ns}	0.14^{ns}	---	0.07^{ns}	0.26^{**}	0.27^{**}	0.15^{ns}	0.87^{**}
IG≥2mm	0.02^{ns}	0.20^{*}	-0.05^{ns}	-0.05^{ns}	0.06^{ns}	-0.16^{*}	---	0.29^{**}	0.35^{**}	0.22^{**}	0.47^{**}
MG≥2mm	0.02^{ns}	0.16^{*}	-0.01^{ns}	-0.04^{ns}	0.15^{ns}	-0.01^{ns}	0.41^{**}	---	0.85^{**}	0.14^{ns}	0.29^{**}
CM≥2mm	0.06^{ns}	0.25^{**}	-0.02^{ns}	-0.02^{ns}	0.15^{ns}	0.04^{ns}	0.40^{**}	0.90^{**}	---	0.64^{**}	0.41^{**}
PR	0.10^{ns}	0.22^{**}	-0.03^{ns}	0.02^{ns}	-0.01^{ns}	0.12^{ns}	0.05^{ns}	-0.04^{ns}	0.40^{**}	---	0.36^{**}
IYG	0.13^{ns}	0.27^{**}	0.11^{ns}	0.05^{ns}	0.14^{ns}	0.70^{**}	0.47^{**}	0.22^{**}	0.40^{**}	0.47^{**}	---

HM: hectoliter mass, MTG: mass of thousand grains, NFT: number of fertile tillers per linear meter, NGP: number of grains per panicle, MGP: mass of grains per panicle, GY: grain yield, IG≥2mm: index of grains larger than 2 mm, MG≥2mm: mass of 300 whole grains larger than 2 mm wide, CM≥2 mm: caryopsis mass of 300 dehulled grains larger than 2 mm wide, PR: peeling rate, IYG: industrial yield of grains. ^{ns} Non significant, * and ** Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively, by t-test.

can slow the genetic progress for industrial yield. In this sense, negative correlations between MTG and NGP in both locations were detected, in Augusto Pestana (r_G= -0.82) and Capão do Leão (r_G= -0.45), indicating a tendency of higher number of grains in the panicle to be accompanied by a lower average grain mass (Table 3). At the same time, in Capão do Leão negative associations of HM with MGP(r_G= -0.61) and NGP (r_G= -0.58) were verified. These associations also indicate difficulty in combining in the same genotype large grain size (mass and volume) and high number of grains per unit area.

No significant genetic correlation and casual relationship between MGP and IYG was observed (Table 3). Although, it is interesting to highlight that meanwhile NGP presented no significant correlation with IYG in Augusto Pestana (r_G= -0.094) and a negative correlation in Capão do Leão (r_G= -0.389) this character showed positive direct effects on the industrial grain yield potential in both locations (0.530 and 0.210, respectively). In Augusto Pestana, an expressive indirect effect of NGP through MG ≥ 2 mm (-0.662) was observed. Therefore, this positive direct effect could be explained by a scenario in which there is the formation of high number of grains in the panicle with consequent reduction of the average grain mass. Nevertheless, this reduction in the average grain mass is not so strong to the point of interfering significantly in the grain average size, maintaining the diameter equal or higher than 2 mm. Thus, the benefits provided on the higher grain yield seem to be able to mitigate the negative effects on grain size, reflecting positive direct effects of number of grains per panicle on the industrial yield values. In this sense, in both locations, MGP presented positive indirect effects on IYG via NGP, while MTG and MG ≥ 2mm showed positive indirect effects on IYG via IG ≥ 2mm. Thus, there is a chance of improvement of industrial yield of grains through the indirect selection of NGP or IG ≥ 2mm when carried out considering both the performance of MGP, or MTG and MG ≥ 2mm, respectively.

The hectoliter mass represents a character of great importance used by the oat breeding programs as the target of selection in order to obtain genotypes with high grain quality (Holland, 1997). However, in both location tested, HM showed correlations of low magnitude and no causal

Table 4. Direct effects and indirect effects on industrial yield of grains (IYG) of characters related to quality and grain production in oat cultivars grown in Augusto Pestana and Capão do Leão, Rio Grande do Sul State, Brazil, in the crop seasons 2007, 2008 and 2009.

Indirect effects of *x* on IYG via *y*	Augusto Pestana - RG									
	(y) HM	MTG	NFT	NGP	MGP	GY	IG≥ 2 mm	MG≥ 2 mm	CM≥ 2 mm	PR
(x) HM	--	-0.025	-0.003	-0.015	0.021	0.068	0.004	0.117	0.176	-0.283
MTG	0.008	--	0.002	-0.433	0.009	-0.154	0.129	0.700	0.365	0.020
NFT	0.067	0.154	--	0.077	0.045	-0.029	-0.196	-0.571	-0.257	-0.166
NGP	-0.002	0.213	-0.001	--	-0.045	0.230	-0.09	-0.662	-0.347	0.001
MGP	-0.024	0.033	0.003	0.329	--	0.203	-0.002	-0.277	-0.208	0.149
GY	0.011	0.081	0.001	0.246	-0.030	--	-0.002	-0.084	0.042	-0.228
IG≥2mm	0.002	-0.183	0.004	-0.259	0.001	-0.005	--	0.637	0.335	0.028
MG≥2mm	0.013	-0.24	0.003	-0.463	0.027	-0.055	0.154	--	0.462	-0.129
CM≥2mm	0.029	-0.192	0.002	-0.371	0.031	0.042	0.124	0.706	--	-0.265
PR	0.055	0.012	-0.002	0.001	0.025	0.265	-0.012	0.230	0.308	--
Direct effect of *y* on IYG	0.083	-0.260	-0.004	0.530	-0.073	0.495	0.184	0.757	0.495	-0.426
r_G with IYG(1)	0.156ns	0.348**	-0.879**	-0.094ns	0.123ns	0.605**	0.772**	0.644**	0.678**	0.393**
Indirect effects of *x* on IYG via *y*	Capão do Leão - RG									
	(y) HM	MTG	NFT	NGP	MGP	GY	IG≥ 2 mm	MG≥ 2 mm	CM≥ 2 mm	PR
(x) HM	--	-0.037	0.265	-0.116	-0.006	0.208	-0.095	0.001	0.008	0.105
MTG	0.006	--	-0.051	-0.090	0.004	0.09	0.264	-0.044	0.034	-0.024
NFT	-0.037	-0.042	--	-0.156	-0.007	0.406	-0.084	0.000	0.005	0.077
NGP	0.024	-0.109	-0.228	--	0.005	-0.197	-0.053	0.027	-0.027	-0.061
MGP	0.025	0.100	-0.241	0.104	--	-0.219	0.162	-0.012	0.005	-0.066
GY	-0.015	0.038	0.209	-0.069	-0.003	--	0.037	-0.004	0.005	0.034
IG≥2mm	0.011	0.186	-0.072	-0.031	0.004	0.061	--	-0.027	0.018	-0.043
MG≥2mm	0.001	0.239	-0.003	-0.123	0.002	0.046	0.21	--	0.035	-0.011
CM≥2mm	-0.008	0.214	0.040	-0.14	0.001	0.080	0.164	-0.041	--	0.055
PR	-0.025	-0.035	0.135	-0.072	-0.004	0.116	-0.089	0.003	0.013	--
Direct effect of *y* on IYG	-0.041	0.242	0.295	0.201	0.009	0.574	0.345	-0.045	0.038	0.168
r_G with IYG(1)	0.286**	0.467**	0.502**	-0.389**	-0.132ns	0.892**	0.504**	0.346**	0.409**	0.236**

HM: hectoliter mass, MTG: mass of thousand grains, NFT: number of fertile tillers per linear meter, NGP: number of grains per panicle, MGP: mass of grains per panicle, GY: grain yield, IG≥2mm: index of grains larger than 2 mm, MG≥2mm: mass of 300 whole grains larger than 2 mm wide, CM≥2 mm: caryopsis mass of 300 dehulled grains larger than 2 mm wide, PR: peeling rate, IYG: industrial yield of grains. (1) ns Non significant, * and **Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively, by t-test. Capão do Leão: coefficient of determination (R^2) = 0.896, residual variable effect = 0.324; Augusto Pestana: coefficient of determination (R^2) = 0.964, residual variable effect = 0.189.

relationship with the IGY (Table 4). Low correlations between hectoliter mass and groat yield have been reported (Buerstmayr et al., 2007). Genotypes that show small grains with high density, characterized by presenting high caryopsis mass concentrated in a smaller volume of grain, can show higher hectoliter mass when compared to genotypes that have lighter grains, explaining the absence of causal relationship of HM on IYG. So, the HM increase does not necessarily ensure the largest groat yield of oat, since the greatest HM needs to be accompanied by the higher grain diameter. A positive correlation of HM with NFT (Augusto Pestana: r_G= 0.81; Capão do Leão: r_G= 0.90) was observed, indicating an association between a higher mass of hectoliter and the increment of fertile tillers per area. Meanwhile, positive correlations between HM and PR were detected (Augusto Pestana: r_G= 0.67; Capão do Leão: r_G= 0.62), agreeing with the results of Doehlert et al. (1999) and Doehlert et al. (2009). Also, a positive correlation between NFT and PR was observed (Augusto Pestana: r_G=0.39; Capão de Leão:r_G= 0.46), highlighting the important relationship of tillering with oat grain quality.

IG ≥ 2 mm showed direct effects on IYG in both locations, with magnitudes lower than the genetic correlations (Capão do Leão: r_G= 0.504, direct effect= 0.345; Augusto Pestana: r_G= 0.772, direct effect= 0.182). The highest magnitude of IG ≥ 2 mm indirect effects were promoted via MG ≥ 2mm (0.637) and via CM ≥ 2 mm (0.335) in Augusto Pestana, and via MTG (0.186) in Capão do Leão. Likewise, other reports have shown positive phenotypic correlation between percentage of oat grains > 2 mm and groat yield (Buerstmayr et al., 2007). MG ≥ 2 mm and CM ≥ 2 mm represent indirect components of the grain industrial yield in oat, and they are very important to determine genotype industrial potentials. In both locations tested, positive phenotypic and genetic correlations between MG ≥ 2 mm x IYG (Capão do Leão: r_G= 0.35; Augusto Pestana: r_G= 0.64) and between CM ≥ 2 mm x IYG (Capão do Leão: r_G= 0.41; Augusto Pestana: r_G= 0.68) were verified (Table 3). In Augusto Pestana, positive direct effects of MG ≥ 2 mm (0.757) and CM ≥ 2 mm (0.495) on IYG were observed, considering the set of oat cultivars evaluated (Table 4). However, such behavior was not observed with the cultivation of the oat cultivars in Capão do Leão, where no significant direct effects were found (-0.045 and 0.038 for MG ≥ 2 mm and CM ≥ 2 mm, respectively).

In the oat crop, the selection of high yield genotypes also showing low hull percentage is sought, since it allows the increase of the relative caryopsis mass, and thereby resulting higher yields of raw material for food processing. However, in both tested locations, low positive correlations and low direct effects of PR in relation to IGY were observed, positive in Capão do Leão (r_G= 0.236, direct effect= 0.168) and negative in Augusto Pestana (r_G= 0.393, direct effect= -0.426) (Table 4). Thus, the PR does not seem to represent an efficient character to be used in the process of indirect selection, aiming at increasing the industrial grain yield. Genotypes that had lower portion of caryopsis erroneously tended to show the highest percentage of caryopsis after mechanical stripping, and also presented fewer breaks with the adoption of mechanical peeling process (Doehlert et al., 1999). According these authors, the presence of thicker hulls promotes greater protection of the grains, and thus favors the smaller number of breaks during the mechanical peeling. Thus, it is very important also evaluate the genotypes regarding caryopsis yield obtained with mechanical peeling, since this is the process adopted commercially, which features one of the currently most important aspects to the suitability of an oat cultivar as raw material for the industrial food processing.

MG $\geq$ 2 mm and NGP stood out by participating expressively via indirect influences on IYG above other characters evaluated in Augusto Pestana. Considering the direct effects on IYG, these characters are important to the definition of industrial yield of grain potential in this location. On the other hand, in Capão do Leão, the direct and indirect effects on IYG presented by the characters were of lower intensity, where the characters seemed to participate with more equitably over the IYG, and GY, IG $\geq$ 2 mm and NFT expressed higher indirect effects.

Despite having shown positive correlation with IYG, the direct positive contribution on IYG of MTG, MG $\geq$ 2 mm, CM $\geq$ 2 mm and PR were not sustained over the locations tested. Meanwhile, GY, IG $\geq$ 2 mm and NGP seem to represent the most promising target characters to be used aiming at the indirect selection of oat genotypes with high grains yield potential destined for industrial food processing. These characters revealed positive direct effects in the definition of industrial yield of grains even with the change of location, suggesting a strong association. However, just the character GY presented high genetic correlations and high positive direct effects on IYG in both locations, indicating that gains obtained on GY by selection process may reflect on gains on IYG.

Materials and Methods

Plant material and experimental environments

In the crop seasons 2007, 2008 and 2009, 15 oat cultivars were tested (all commercial cultivars): Albasul, Barbarasul, Brisasul, FAPA Louise, UPF 15, UPF 16, UPF 18, UFRGS 14, UFRGS 19, UPFA 20, UPFA 22, URS 20, URS 21, URS 22 and URS. The experiments were conducted in the Rio Grande do Sul state, in the counties of Augusto Pestana (latitude 28º 27’ S, longitude 53º 54' W, altitude 328 m) in a Typic Dystrophic Red Latosol; and in Capão do Leão(latitude 31º 45’ S, longitude 52º 29’ W, altitude 13 m) in a Dystrophic Yellow Red Argisol (Santos et al., 2006).

Experimental conditions

The soil preparation, liming and fertility correction were made following the oat technical recommendations for cultivation in Brazil (BORC, 2006). The fertilization corrections with macronutrients were performed according to the levels observed in the soil chemical quality analysis in each year of cultivation to supply the demands of the culture for a 2.0 t ha^{-1} grain yield (Table 1). Tebuconazole fungicide applications at a dosage of 0.75 L ha^{-1} were performed according to the need for shoot disease control during the crop cycle.

All experiments were conducted following a randomized block design with four replications, adopting a density of 250 viable seeds per square meter, with replicates formed by plots with five rows 5.0 m long spaced in 0.20 m, with the measurements without edge effects made in three core lines, featuring 3.0 m^2 plots.

Character assessment

At the end of the growing season, the number of fertile tillers per linear meter (NFT, in units) was measured. From the plot grain harvested, grain yield (GY, kg ha^{-1}), mass of thousand grains (MTG, g) and hectoliter mass (HM, 100 kg L^{-1}) were determined. Based on ten panicles taken at random in the plot, mass of grains per panicle (MGP, g) and number of grains per panicle (NGP, in units) were measured. A sample of 100 whole grains from each plot was sifted quantifying the number of grains smaller and larger than 2 mm wide, and the index of grains larger than 2 mm (IG $\geq$ 2 mm, dimensionless) was obtained. The mass of 300 whole grains larger than 2 mm wide was obtained (MG $\geq$ 2 mm, g), and the caryopsis mass (CM $\geq$ 2 mm, g) was defined after manually peeling the grains. Consequently, the peeling rate (PR, dimensionless) was determined by the ratio between CM $\geq$ 2 mm and MG $\geq$ 2 mm. The industrial yield of grains (IYG, in kg ha^{-1}) was determined by multiplying the grain yield in the plot, the rate of grains larger than 2 mm wide and the peeling rate (IYG = GY x IG $\geq$ 2 mm x PR), corresponding to the fraction of harvested grain proper to be used by the human food industry.

Statistical analysis

For each location of evaluation separately, considering the behavior of the oat cultivars along three seasons of cultivation (2007, 2008 and 2009), the coefficients of phenotypic (r_P), genetic (r_G) and environment (r_E) correlations among all traits were estimated using the expected mean square [E (MS)] by variance analysis, as described by Falconer and Mackay (1996). The variance analysis and correlation estimates were obtained considering the randomized block design with four replications, and the treatments year and genotype were considered as fixed effects. The significance of the magnitude of correlation coefficients was tested at 1 and 5% probability by t-test, as described by Steel and Torrie (1980). The genetic correlations (r_G) were partitioned into direct and indirect effects of traits (explanatory variables in the regression model) on industrial yield of grains (basic variable) through path analysis (Wright, 1921).The degree of multicollinearity of the singular matrix X'X was established based on its number of conditions, which is the ratio between the highest and the lowest eigenvalue of the matrix of genetic correlations (Montgomery and Peck, 1981). The analysis of the genetic correlation matrix eigenvalues was performed to identify the nature of the linear dependence among the traits, detecting those that contributed to the occurrence of multicollinearity (Belsley et al., 1980). All procedures and analysis were run on the GENES software (Cruz, 2013).

Conclusions

Estimates of correlations and causal relationship of traits in the industrial yield of grains in oat cultivars were modified in response to each location. The hectoliter mass does not show a causal association with industrial yield, despite being widely used as target of selection for grain quality by oat breeding programs. The indirect selection process performed by associating the number and mass of grains per panicle could improve the genetic gain on grain industrial yield. Also, genotype performance for index of grains larger than 2 mm and mass of thousand grains or mass of 300 whole grains larger than 2 mm can be used to improve industrial yield. Given the stable positive correlation and causal relationship, grain yield seems to represent the most successful character to be used in strategies of indirect selection aiming the improvement of oat grain industrial yield.

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